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Ms. Magalie Roman Salas
Secretary
Federal Communications Commission
The Portals
445 Twelfth Street, S.W.
Room TW-A325
Washington, DC 20554

Re: Revision of Part 15 of the Commission's Rules Regarding Ultrawideband Transmission Systems, ET Docket No. 98-153

Dear Ms. Salas:

Forwarded to you for inclusion in the public record of the above-referenced docket, enclosed please find five copies of the "Observations regarding Test Data Collected at University of Texas Applied Research Laboratory on GPS Receivers Operating in the Presence of Ultrawideband Emissions" prepared by the Department of Defense Joint Spectrum Center on behalf of the Interagency GPS Executive Board. (IGEB). The IGEB requested that the National Telecommunications and Information Administration forward this report to the Commission for inclusion in the public record of the above-referenced proceeding.

Please direct any questions you may have regarding this filing to the undersigned. Thank you for your cooperation.

Respectfully submitted,

Kathy D. Smith

Kathy D. Smith
Chief Counsel

Enclosures

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JSC-CR-01-036

DEPARTMENT OF DEFENSE
JOINT SPECTRUM CENTER
ANNAPOLIS, MARYLAND 21402-5064

OBSERVATIONS REGARDING TEST DATA COLLECTED AT UNIVERSITY OF TEXAS APPLIED RESEARCH LABORATORY ON GPS RECEIVERS OPERATING IN THE PRESENCE OF ULTRAWIDEBAND EMISSIONS

Prepared for

INTERAGENCY GPS EXECUTIVE BOARD
WORKING GROUP 3
IGEB Executive Secretariat
4805 Herbert C. Hoover Building
Washington, DC 20230

JSC Project Engineer

Frederick Moorefield and Steve Molina

MAY 2001

CONSULTING REPORT

Prepared by

Michael Dion

IIT Research Institute
Under Contract to
Department of Defense

Approved for public release; distribution is unlimited.

This report was prepared by the IIT Research Institute under Contract DCA100-00-C-4012 in support of the DoD Joint Spectrum Center in Annapolis, Maryland.

This report has been reviewed and is approved for publication.

Reviewed by:

MICHAEL DION
Project Manager

JOHN R. SMITHMYER
Division Manager

Approved by:

RICHARD B. LARSON
Deputy Commander

R M Williams Jr
for
SAMUEL G. CARBAUGH
Lt Col, USAF
Chief, Acquisition Support

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13. ABSTRACT (Maximum 200 words)

The Joint Spectrum Center (JSC) was tasked by the Interagency GPS Executive Board Working Group 3 (IGEB WG3) to review a set of test data collected on GPS receivers operating in the presence of ultrawideband (UWB) signals. The subject data was collected by the Applied Research Laboratory at the University of Texas (ARL UT). The IGEB WG3 specifically requested that the JSC focus on comparing these test results to results obtained by the National Telecommunications and Information Administration (NTIA) in a separate GPS-UWB test effort.

This report contains an overview of the test approach, a description of the data, and the requested comparison of results. The comparison is based on the UWB power levels that caused the GPS receivers to break lock on the desired signal during tracking tests. Data for four of the six receivers tested at ARL UT was found to be usable for this comparison. For three of the four receivers, the results obtained with UWB interference were found to be consistent with the results obtained by NTIA for UWB interference that was characterized as noise-like. The UWB results for the fourth receiver were found to be noticeably non-noise-like. For this receiver, several other GPS receiver performance metrics were examined to investigate how the UWB effects differ from the effects produced by continuous white noise. This more detailed examination of the test results clearly showed effects that were more characteristic of narrowband or continuous wave (CW) interference than they were of noise-like interference. This observation is important because, for a given amount of interference power in the GPS receiver passband, GPS receivers are typically more susceptible to narrowband interference than to broadband noise interference.

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EXECUTIVE SUMMARY

The Federal Communications Commission (FCC) is considering proposals to modify its rules to permit the operation of certain ultrawideband (UWB) devices under Part 15 of Title 47 of the Code of Federal Regulations. Due to the unusually large occupied bandwidth of UWB device emissions, the potential exists for interference to a wide variety of systems operating over large portions of the radio frequency (RF) spectrum. The Global Positioning System (GPS) is one such system that could potentially be affected by the introduction of UWB emissions into the RF environment.

Three major test efforts have been undertaken to begin to address the electromagnetic compatibility (EMC) issues related to UWB signal effects on GPS receiver performance. One effort was funded and performed by the National Telecommunications and Information Administration (NTIA). Another was funded by the Department of Transportation (DOT) and performed by Stanford University. A third effort was funded by Time Domain Corporation (TDC), a developer of UWB technology, and performed by the Applied Research Laboratory at the University of Texas (ARL UT). The ARL UT effort differed from the other two efforts in that ARL UT was tasked only to collect the data. This data was made available to the public through the ARL UT Internet site so that interested parties could have access to this data for their respective analyses. TDC subsequently tasked the Johns Hopkins University Applied Physics Laboratory (JHU APL) to analyze this data.

The Interagency GPS Executive Board Working Group 3 (IGEB WG3), which deals primarily with GPS spectrum defense issues, is concerned as to whether or not the emissions from UWB would be compatible with GPS operation. IGEB WG3 has received briefings from NTIA and DOT on their respective test efforts, but has lacked information on the ARL UT results. The IGEB WG3 determined that reviewing the ARL UT test data independently of the industry-sponsored analysis would be in its best interest. Therefore, the IGEB WG3 tasked the Joint Spectrum Center (JSC) to conduct such a review. The IGEB WG3 further requested the JSC to focus on a comparison of the ARL UT results to those obtained by NTIA.

This report contains an overview of the test approach, a description of the data, and the requested comparison of results. The comparison is based on the UWB power levels that caused the GPS receivers to break lock on the desired signal during tracking tests. Data for four of the six receivers tested at ARL UT was found to be usable for this comparison. For three of the four receivers, the results obtained with UWB interference were found to be consistent with the results obtained by NTIA for UWB interference that was characterized as noise-like. The UWB results for the fourth receiver were found to be noticeably non-noise-like. For this receiver, several other GPS receiver performance metrics were examined to investigate how the UWB effects differ from the effects produced by continuous white noise. This more detailed examination of the test results clearly showed effects that were more

characteristic of narrowband or continuous wave (CW) interference than they were of noise-like interference. This observation is important because, for a given amount of interference power in the GPS receiver passband, GPS receivers are typically more susceptible to narrowband interference than to broadband noise interference.

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GLOSSARY

ARL UT	Applied Research Laboratory at the University of Texas
C/A	Coarse Acquisition
C/N_O	Carrier-to-noise density ratio
CW	Continuous wave
dB	Decibels
dBi	Decibels relative to an isotropic antenna
dBm	Decibels relative to a milliwatt
DOT	Department of Transportation
EMC	Electromagnetic compatibility
FCC	Federal Communications Commission
GPS	Global Positioning System
IGEB WG3	Interagency GPS Executive Board Working Group 3
JHU APL	Johns Hopkins University Applied Physics Laboratory
JSC	Joint Spectrum Center
kHz	Kilohertz
MHz	Megahertz
ms	Millisecond
ns	Nanosecond
NMEA	National Marine Electronics Association
NTIA	National Telecommunications and Information Administration
PAD	PulsON Applications Developer
PDOP	Position dilution of precision
%	Percent
PRF	Pulse repetition frequency
RF	Radio frequency
RMS	Root-mean-squared
S/I	Signal-to-interference ratio
S/(I+N)	Signal-to-interference plus the noise
SV	Space vehicle
TDC	Time Domain Corporation (a developer of UWB technology)
UTC	Universal time coordinated
UWB	Ultra-wideband

SECTION 1 - INTRODUCTION

BACKGROUND

The Federal Communications Commission (FCC) is considering proposals to modify its rules to permit the operation of certain ultrawideband (UWB) devices under Part 15 of Title 47 of the Code of Federal Regulations. Due to the unusually large occupied bandwidth of UWB device emissions, the potential exists for interference to a wide variety of systems operating over large portions of the radio frequency (RF) spectrum. The Global Positioning System (GPS) is one such system that could potentially be affected by the introduction of UWB emissions into the RF environment.

Three major test efforts have been undertaken to begin to address the electromagnetic compatibility (EMC) issues related to UWB signal effects on GPS receiver performance. One effort was funded and performed by the National Telecommunications and Information Administration (NTIA). Another was funded by the Department of Transportation (DOT) and performed by Stanford University. A third effort was funded by Time Domain Corporation (TDC), a developer of UWB technology, and performed by the Applied Research Laboratory at the University of Texas (ARL UT). The ARL UT effort differed from the other two efforts in that ARL UT was tasked to collect the data but not to perform any analysis or to develop any recommendations. This data was made available to the public through the ARL UT Internet site[1] so that interested parties could have access to this data for their respective analyses. The data was posted in the raw format provided by each GPS receiver. TDC subsequently tasked the Johns Hopkins University Applied Physics Laboratory (JHU APL) to analyze this data.

The Interagency GPS Executive Board Working Group 3 (IGEB WG3), which deals primarily with GPS spectrum defense issues, is concerned as to whether or not the emissions from UWB would be compatible with GPS operation. IGEB WG3 has received briefings from NTIA and DOT on their respective test efforts, but has lacked information on the ARL UT results. Based on available information regarding the ARL UT test approach, the IGEB WG3 was concerned that a comprehensive evaluation of the EMC of UWB signals with GPS receivers could not be performed from the resulting test data. However, the IGEB WG3 determined that reviewing the ARL UT test data independently of the industry-sponsored analysis would be in its best interest. Therefore, the IGEB WG3 tasked the Joint Spectrum Center (JSC) to conduct such a review.

Because test reports would ultimately be published and submitted to the FCC as part of the review process for the proposed rules, the IGEB WG3 saw the need to be able to interpret, compare, and

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[1] "Test Plan for UWB/GPS Compatibility Effects" [ARL UT Web Page], Austin, TX: ARL UT, 18 December 2000 [cited 16 March 2001]. Available from http://sgl.arlut.utexas.edu/asd/Cure/testplan.html.

comment on these reports. However, because of the differences in test conditions and methodologies used in the various test efforts, a comparison of even the basic test results (e.g., receiver performance metrics versus UWB power level) could not be accomplished by inspection. The consistency, or lack thereof, of the basic test results was deemed to be an important reference point for the comparison of analysis results (e.g., prediction of allowable UWB device EIRP). Therefore, after a preliminary review of results, the IGEB WG3 requested that the JSC focus on a comparison of the ARL UT test results to the test results of the NTIA test effort. This report provides the requested comparison of test results. Information on the NTIA tests was obtained from NTIA Special Publication 01-45.[2] The information on the ARL UT tests was obtained from the raw data files posted on the ARL UT Internet site and from ARL UT Laboratory Report TL-SG-01-01, which provides information on how the data was collected.[3]

OBJECTIVE

The objective of this task was to provide an overview of the UWB-GPS test data collected by ARL UT and to compare these results to the NTIA test results.

APPROACH

The first major portion of this effort was the review of the test documentation (Reference 1-3) and other available information regarding the ARL UT test conditions and procedures. Knowledge of the test conditions, procedures, and data format was needed to enable any type of analysis. A description of key elements of the ARL UT tests was developed and is included in Section 2.

The ARL UT test data was made available in raw form. As each test was conducted, the raw outputs from each receiver were logged to a data file. Each receiver updated the output values of all quantities provided by that receiver once per second. The total data set includes four different data formats, three of which are binary and one of which is text. Therefore, the second major part of this effort was the development of utilities to convert this data to a format in which it could be analyzed readily. This in turn was a two-part effort. The first step was to develop utilities to extract key parameters from the raw data files into a common database structure. The second step was to develop spreadsheet utilities to access data from the database, process it, and generate plots of

[2] Steven K. Jones, Edward Drocella, David Anderson, and Mark Settle, *Assessment of Compatibility Between Ultrawideband (UWB) Systems and Global Positioning System (GPS) Receivers*, NTIA Special Publication 01-45, Washington, DC: National Telecommunications and Information Administration, February 2001.

[3] Miguel Cardoza, Douglas Cummings, and Aaron Kerkhoff, *Final Report, Data Collection Campaign for Measuring UWB/GPS Compatibility Effects*, TL-SG-01-01, Austin, TX: Applied Research Laboratory University of Texas at Austin, February 2001.

receiver output quantities as a function of time. An overview of the database and data processing methods is provided in Section 3.

Once the capabilities to access and display the data were developed, these capabilities were used to compare the results of the ARL UT tests to the results of the NTIA tests. This portion of the effort required the identification of appropriate subsets of the data as the basis for the comparison. It also required a determination of the adjustments necessary to account for differences in the test methodologies. The results of this comparison are provided in Section 4. Section 5 presents a more detailed description of the ARL UT test results that were found to disagree substantially with the NTIA results for noise-like UWB signals.

SECTION 2 - DESCRIPTION OF ARL UT TEST METHODS AND DATA COLLECTED

OVERVIEW

The ARL UT test program included laboratory bench tests and outdoor field tests. In the laboratory bench tests, a GPS simulator provided the GPS signals and a PulsON Applications Developer (PAD) provided the UWB signals. Tests were also conducted with a broadband white noise source instead of the PAD and with no undesired signals present. The same GPS scenario was used for each of these tests. The GPS and UWB (or white noise) signals were applied to the receivers under test through direct cable connections. These tests were referred to as the conducted signal tests. In the outdoor field tests, the available GPS signals from the actual satellites were used. A variety of UWB devices, including the PAD provided the UWB signals, and the broadband white noise source was also used. The receivers under test were placed in an open field and the GPS and UWB signals were applied to the receivers through the antenna. These tests were referred to as the radiated tests. Because the radiated tests used whatever GPS constellation was present at the time of each test, the GPS signal conditions varied from test to test.

In both the conducted and radiated tests, GPS receiver ranging and acquisition performance were evaluated using separate test methods. The ranging tests (also referred to as tracking tests) evaluated performance with regard to tracking space vehicles (SVs) that have already been acquired by the receiver. The loss of tracking in these tests is referred to as breaklock. The acquisition tests evaluated the ability of the receiver to reacquire SVs after the desired signals had been denied to the receiver for a short period of time.

This analysis focused on the conducted signal test data because the conducted signal tests represent a more controlled experiment than the radiated tests and because a primary goal of this effort was to compare the ARL UT results to those of the NTIA tests, which used conducted signals. This section summarizes the conducted test data collection methodology and provides a description of the data. A more detailed presentation of the complete test approach is provided in Reference 1-3.

TEST CONFIGURATION

Equipment Setup

Figure 2-1 is a simplified block diagram of the conducted signal test setup. The desired GPS signal from the GPS simulator is combined with the undesired UWB signal from the PAD or the white noise signal from the white noise generator. Note that two such test setups were actually used in the test program. The first setup, which included a 12-channel GPS simulator, was used for four of the six GPS receivers tested. These receivers were tested by ARL UT in a laboratory at Holoman Air Force Base. The second setup, which included a 10-channel GPS simulator, was used to test the remaining two receivers. These receivers were tested at ARL UT using a borrowed GPS simulator.

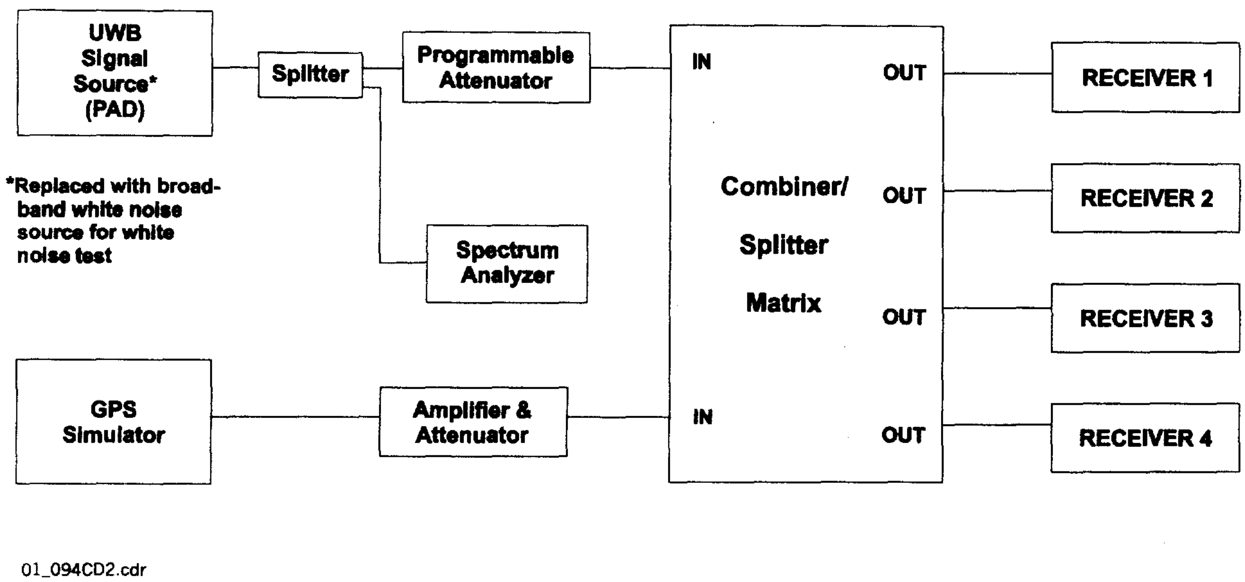

Figure 2-1. Simplified Block Diagram of ARL UT Test Configuration

In the ranging tests, the GPS power levels at the receiver inputs remained constant throughout the test and the attenuator in the UWB signal path was used to vary the UWB power levels to the receivers. In the acquisition tests, the attenuator in the UWB signal path was used to set the UWB power level for each acquisition trial and the attenuator in the GPS signal path was used to turn the GPS signals on and off.

GPS Receivers

The ARL UT test program was planned to include seven GPS receivers from five different manufacturers. However, one of the receivers was found to interfere with the operation of the others in the test setup. This problem was caused by excessive leakage of RF signals produced by and used within the receiver. Therefore, six receivers from four manufacturers were actually tested. The receivers are listed in Table 2-1. Note that the receiver numbering convention adopted by ARL UT in Reference 1-3 is used in this report for consistency.

Table 2-1. GPS Receivers Used in ARL UT Test Effort

Receiver Reference	Nomenclature
Receiver 1	NovAtel 3151
Receiver 2	Ashtech Z-12
Receiver 3	Garmin GPS 150 XL
Receiver 4	Ashtech Z-Sensor
Receiver 6	NovAtel Millennium
Receiver 7	Trimble 4700

GPS Scenarios

All of the conducted signal tests used static GPS scenarios, which means that no motion of the GPS receiver was simulated. However, the usual motion of the GPS satellites was simulated. The simulated receiver position was given in Reference 3 as 30 degrees 23.045468817 minutes north latitude, 97 degrees 43.6368709832 minutes west longitude, at an altitude of 207.601948869 meters. The simulated start time for all the conducted signal tests was 06:00:00, 26 July 2000 GPS time. The maximum test duration was approximately eight hours.

Three basic GPS scenarios were defined. The difference between them was the simulated GPS power level at the GPS receiver input. The first scenario, referred to as the live sky scenario, was intended to represent typical GPS power levels and was used for ranging tests. The second scenario, referred to as the minimum level scenario, was intended to represent the minimum guaranteed GPS power level, and was also used for ranging tests. The third scenario was used for acquisition tests and was referred to as the acquisition scenario. The two ranging test scenarios were implemented in both test setups. However, because of the different capabilities of the simulators with regard to the maximum number of SVs that can be simulated, the resulting scenarios were different in the two setups. In the setup with the 12-channel simulator, all SVs that would be expected to be visible at the simulated location and time over the course of the test were simulated. In the setup with the 10-channel simulator, one or more SVs that would normally be visible had to be dropped from the constellation for certain time intervals in the simulation to keep the total number of simulated SVs to ten or less. The acquisition scenario was used only in the test setup with the 12-channel simulator.

The GPS power levels used in the live sky scenario were derived based on the average carrier-to-noise density ratio (C/N_0) output from each receiver when operating in an outdoor, open-field environment with no known interfering signals present. For the simulated live sky scenario, the GPS power level at the input to each receiver in the setup was set so that the receiver provided the same average C/N_0 output as in the outdoor environment. The GPS power levels used in the minimum level scenario were simply 13 decibels (dB) weaker than those used in the live sky scenario in the test setup used for Receivers 1 through 4. The GPS power levels used in the acquisition scenario for this test setup were 7 dB stronger than those in the minimum level scenario. In the test setup for

Receivers 6 and 7, the minimum level scenario used levels that were 12 dB weaker than those used in the corresponding live sky scenario. The GPS power levels used for the conducted signal tests are summarized in Table 2-2.

Table 2-2. GPS Power Levels Used in ARL UT Test Effort

	Live Sky Scenario		Minimum Level Scenario		Acquisition Scenario	
Receiver	GPS L_1 Power (dBm)	GPS L_2 Power (dBm)	GPS L_1 Power (dBm)	GPS L_2 Power (dBm)	GPS L_1 Power (dBm)	GPS L_2 Power (dBm)
Receiver 1	-116.8	-115.9	-129.8	-128.9	-122.8	-121.9
Receiver 2	-111.1	-110.3	-124.1	-123.3	-117.1	-116.3
Receiver 3	-123.6	-122.6	-136.6	-135.6	-129.6	-128.6
Receiver 4	-111.1	-110.2	-124.1	-123.2	-117.1	-116.2
Receiver 6	-133.5	-134.4	-145.5	-146.4	n/a	n/a
Receiver 7	-112.1	-113.1	-124.1	-125.1	n/a	n/a

The normalization of simulated GPS power levels based on the receiver C/N_0 output did not ensure that the absolute GPS power input to the receiver in the live sky scenario was the same as in the actual outdoor setting. The antennas used in the outdoor setting included integral preamplifiers that were not present in the laboratory setting. The C/N_0 output from the receiver in the outdoor case would be determined by the GPS power level arriving at the preamplifier input and by the preamplifier noise figure, and would not necessarily provide an indication of the absolute GPS power level at the receiver input. The relationship between the GPS power level at the preamplifier input and the corresponding level at the receiver input would be a function of the preamplifier gain and the cable loss. As long as the cable loss is several dB less than the preamplifier gain minus the noise figure, the cable loss can vary without changing the C/N_0. Therefore, a particular C/N_0 value can correspond to a range of absolute GPS power levels at the GPS receiver input. In the conducted signal tests, the system noise floor was determined by the effective GPS receiver input thermal noise. In this case, the C/N_0 is a function of the absolute GPS power level at the receiver input. By the same argument, the GPS power levels used in the minimum level scenario did not necessarily correspond to the guaranteed minimum GPS power level, which is defined (for GPS L_1) as -130 dBm at the output terminals of a 0 dBi (decibels relative to an isotropic antenna) receiving antenna.

The GPS power levels used for Receiver 6 in the minimum level scenario are observed to be unreasonably weak, being approximately 15 dB weaker than the guaranteed minimum GPS power level. Successful receiver operation would not be expected at this power level, yet the test data indicates that the receiver did operate satisfactorily with this scenario. Therefore, the validity of the data collected on Receiver 6 is in doubt.

UWB Signals

The UWB signals used for these tests were all based on the same waveform and modulation scheme. The basic waveform was an impulse with a 50 percent (%) pulsewidth of 0.5 nanoseconds (ns). The modulation consisted of pseudorandomly "dithering" the pulse positions over a 25 ns range about the nominal period between impulses. The code length for this pseudorandom dither was 1024. The UWB signal variations included pulse repetition frequencies (PRFs) of between 1 and 10 megahertz (MHz), burst duty cycles between 25 and 100%, and burst periods between 2 and 20 milliseconds (ms). The UWB signal parameters used in the ARL UT tests are summarized in Table 2-3. Note that for burst duty cycles other than 100%, the stated PRF refers to the PRF during the burst "on" time.

Table 2-3. UWB Signal Variations Used in ARL UT Test Effort

UWB Mode	Nominal PRF (MHz)	Duty Cycle (%)	Burst Period (ms)	Burst On Time (ms)
1	1	100	continuous	0
2	1	50	2	1
3	1	50	8	4
4	1	50	20	10
5	1	25	8	2
6	1	66	12	8
7	5	100	continuous	0
8	5	50	2	1
9	5	50	8	4
10	5	50	20	10
11	5	25	8	2
12	5	66	12	8
13	10	100	continuous	0
14	10	50	2	1
15	10	50	8	4
16	10	50	20	10
17	10	25	8	2
18	10	66	12	8

As was the case with the GPS power levels, the UWB power levels were different for the various receivers. Table 2-4 lists the UWB power levels at each receiver input for a 0 dB programmable attenuator setting (see Figure 2-1) for the three 100% duty cycle UWB modes used in the tests. The broadband white noise power levels used in the white noise tests are also shown in the table. The power levels are presented in terms of the "log average" power spectral density in dBm/MHz, as measured on a spectrum analyzer at the GPS L_1 frequency of 1575.42 MHz using a resolution bandwidth of 1 MHz and a video bandwidth of 1 kilohertz (kHz) (video averaging technique). The power levels for each PRF shown in Table 2-4 are also applicable to the other UWB modes at the same PRF if they are interpreted as being the log average power spectral density during the burst "on" time.

Table 2-4. UWB Power Levels at GPS Receiver Inputs for 0 dB Attenuator Setting

Receiver	UWB Mode 1 (1 MHz PRF) Power (dBm/MHz)	UWB Mode 7 (5 MHz PRF) Power (dBm/MHz)	UWB Mode 13 (10 MHz PRF) Power (dBm/MHz)	Continuous White Noise Power (dBm/MHz)
Receiver 1	-91.3	-83.6	-81.0	-81.1
Receiver 2	-85.9	-78.3	-75.7	-75.8
Receiver 3	-98.1	-90.5	-87.9	-88.0
Receiver 4	-85.7	-78.0	-75.4	-75.5
Receiver 6	-114.4	-106.8	-104.2	-104.3
Receiver 7	-80.4	-72.8	-70.1	-70.2
Note: Stated power levels are "log average" measured with a spectrum analyzer at 1575.42 MHz with resolution bandwidth = 1 MHz and video bandwidth = 1 kHz. The term "log average" implies that these values have not been corrected to account for the spectrum analyzer logarithmic detector function.				

Over the course of each ranging test or series of acquisition tests, the UWB power level was varied using the programmable attenuator in the UWB signal path (see Figure 2-1). The acquisition tests used 5 dB steps starting at 45 dB and ending with 5 dB. The ranging tests used the following attenuator settings:

- 60 dB
- 43 to 22 dB in 3 dB increments
- 20 to 0 dB in 2 dB increments.

TEST APPROACH

The conducted signal tests at ARL UT included ranging tests with the live sky and minimum level GPS scenarios and acquisition tests with the acquisition scenario. All of these test types were conducted with the following three types of interference conditions:

1. Baseline (i.e., no interference)
2. White noise
3. UWB signals.

Each conducted signal test began at the same simulated location and time. Therefore, the baseline test results provide a reference point for the evaluation and direct comparison of the effects of the UWB and white noise signals on the GPS receiver performance. All 18 UWB signal modes were used for the ranging tests using the minimum level scenario. The live sky ranging tests and all of the acquisition testing used smaller sets of selected UWB modes. Each test was conducted using a specific GPS scenario and interference signal type.

In each ranging test, the GPS receivers were allowed to acquire and track the GPS signals before the UWB or white noise signal was turned on. Initially, the attenuator in the UWB signal path (see Figure 2-1) was set to the maximum value of 60 dB and the UWB or white noise signal was turned on. Then, the attenuation was progressively reduced to 0 dB as the test proceeded. Each attenuation step was maintained for at least 20 minutes while the output data stream from each receiver was stored to a file. Data recording was interrupted between each 20 minute sampling interval while the test controller (computer) performed other functions (e.g., collecting spectrum plots of the UWB signal). The duration of these interruptions varied from test to test, ranging from a few seconds to a few minutes. However, 20 minutes of data was obtained from each receiver at each attenuator setting (except when breaklock occurred, in which case the receiver ceased to provide data). The data from each 20 minute recording interval for each receiver was saved to a separate file.

Each acquisition test consisted of a series of 30 acquisition attempts at each of nine different UWB attenuator settings. The GPS receivers were allowed to acquire the GPS signals at the start of the test (with the UWB signals turned off). Once testing with the UWB signals began, the UWB signal generator remained on, and for each set of 30 trials, the UWB attenuator setting remained constant. For each individual trial, the receivers were allowed to track the GPS signal for 10 seconds (assuming they had previously acquired the signal) at the start of the trial. Then, the attenuator in the GPS signal path was set to its maximum value to effectively turn off the GPS signal to the receivers. This outage lasted for 30 seconds to ensure that all of the receivers had ceased to track the GPS signal. The GPS signal was then restored for 3 minutes to allow the receivers to attempt a reacquisition of the lost GPS signals. The data output from each receiver for each individual acquisition trial was logged to a separate file.

POWER LEVEL CONSIDERATIONS

Because of the issues noted in the "GPS Scenarios" section regarding the difficulty in correlating the GPS power levels used in the tests to the absolute power levels in a real world scenario, great care must be exercised in the interpretation of results. Because a good correlation to real world conditions exists only for the C/N_0, the UWB power levels must be considered in terms of the level relative to the GPS power levels. Once the signal-to-interference ratio (S/I) that produces a particular effect is determined, this value can be used to calculate the interference power level that would produce that same effect for different values of (desired GPS) signal power, as long as the interference power level calculated in this manner remains substantially above the effective preamplifier input noise. As the calculated interference power approaches the effective input noise level, one must consider the ratio of the signal to the interference plus the noise [S/(I+N)].

The following example illustrates how the test results can be calibrated to a desired absolute power reference, which in this case is the guaranteed minimum GPS power level. If some particular effect is observed in the test results for Receiver 2 with the minimum level scenario at a white noise power level of -90 dBm/MHz, then the S/I is the GPS power level (-124 dBm from Table 2-2) minus the interference power level. Thus:

S/I = -124 dBm - (-90 dBm/MHz) = -34 dB-MHz.

To determine the white noise power level that would produce the same observed effect under the actual minimum GPS signal level condition, the calculated S/I, in dB-MHz, must be subtracted from the minimum guaranteed GPS signal level of -130 dBm. Thus:

-130 dBm minimum GPS power - (-34 dB-MHz S/I) = -96 dBm/MHz.

This power level refers to the same reference point at which the GPS power level is defined, which is the output port of a 0 dBi receiving antenna. This does not imply that the GPS power level would be -130 dBm at the input to Receiver 2. This power level would be present at the input to the external preamplifier, assuming negligible cable loss between the antenna and preamplifier.

Appropriate adjustments can be made as necessary if the antenna gain in the direction of the UWB source is different from the gain in the direction of the GPS SV, or to account for differences in polarization loss. Note that if the GPS preamplifier has a noise figure of 3 dB, the calculated interference power of -96 dBm/MHz is 15 dB above the input noise level of approximately -111 dBm/MHz. Therefore, S/(I+N) is approximately equal to S/I and the conversion is valid.

Using logarithmic units (e.g., dBm, dBm/MHz) for all power levels, a more simply stated method for performing these calculations is to:

1. subtract the GPS power level used in the test from the operational GPS power level of interest
2. subtract the resulting value from the interference power level that produced the effect of interest during the test.

The result is the predicted interference power level that will produce the effect of interest in the presence of the particular operational GPS power level.

RAW DATA

GPS Receiver Data

The data for all of the receivers except Receiver 3 was provided in binary, manufacturer-specific format. Receiver 3 provided output in an ASCII format defined by the National Marine Electronics

Association (NMEA), referred to as NMEA 0183. In all cases, the output consisted of one or more records, or "sentences," produced once per second. Each sentence contains several data items. Some sentences provide data related to the navigation solution, including position, velocity, and position dilution of precision (PDOP). Other sentences provide satellite-specific data such as pseudorange, carrier phase, Doppler shift, signal strength, and some type of indication of detected cycle slips within the receiver. Table 2-5 lists the sentences provided in each receiver's output, along with an indication of which key quantities can be extracted from each sentence.

Table 2-5. GPS Receiver Data Output

Receiver	Sentence	Information Provided
Receiver 1	RGEB	Pseudorange, carrier phase, Doppler shift, signal strength, cycle slips
	SATB	SV azimuth and elevation, SV used in solution
Receiver 2	MPC	Pseudorange, carrier phase, Doppler shift, signal strength, cycle slips
	RPC	Pseudorange, carrier phase
	PBN	Position, PDOP, clock offset
Receiver 3	$GPGGA	Position
	$GPGSA	PDOP, SVs used in solution
	$GPGSV	SV azimuth and elevation, signal strength
	$GPRMB	Miscellaneous navigational information
	$GPRMC	Miscellaneous navigational information
Receiver 4	MPC	Pseudorange, carrier phase, Doppler shift, signal strength, cycle slips
	PBN	Position, PDOP, clock offset
Receiver 6	RGEB	Pseudorange, carrier phase, Doppler shift, lock time
Receiver 7	Record 11	Position, PDOP, clock offset
	Record 17	Clock offset, pseudorange, carrier phase, Doppler shift, signal strength, cycle slips, SV azimuth and elevation, SVs used in solution

UWB Signal Characterization Data

The posted data from the ARL UT test effort includes amplitude versus frequency data for the UWB signals. This data was obtained with the spectrum analyzer in the test setup (see Figure 2-1). In the early phases of testing, a series of spectrum analyzer plots were obtained between each change in test conditions (i.e., between each UWB power level step). Because the UWB signal was sampled prior to the attenuators, all of the data obtained for each UWB mode was essentially the same. Therefore, a single, complete set of plots suffices to represent all of the spectral data collected on the UWB signals. Table 2-6 summarizes the spectrum analyzer settings that were used to obtain the data. The 16 different spectrum analyzer configurations listed in Table 2-5 were used with each of the 18 UWB modes.

Table 2-6. Spectrum Analyzer Settings Used to Characterize UWB Signals

Center Frequency	Resolution Bandwidth	Video Bandwidth	Frequency Span	Sweep Time
3 GHz	1 MHz	3 MHz	6 GHz	130 ms
	1 MHz	1 kHz	6 GHz	15 s
1575.42 MHz (GPS L_1)	1 MHz	3 MHz	2 MHz	50 ms
			20 MHz	50 ms
	1 MHz	1 kHz	2 MHz	50 ms
			20 MHz	50 ms
	1 kHz	300 Hz	10 kHz	200 ms
			100 kHz	840 ms
			200 kHz	1.7 s
1227.6 MHz (GPS L_2)	1 MHz	3 MHz	2 MHz	50 ms
			20 MHz	50 ms
	1 MHz	1 kHz	2 MHz	50 ms
			20 MHz	50 ms
	1 kHz	300 Hz	10 kHz	200 ms
			100 kHz	840 ms
			200 kHz	1.7 s

SECTION 3 - DATA PROCESSING

OVERVIEW

To facilitate the manipulation and analysis of the data for all of the receivers used in the ARL UT test program, a common database structure was developed and the data for each receiver was extracted from its original data format and placed in that structure. The database application used for this analysis was Paradox 8. Analysis of the data was accomplished using the Microsoft Excel spreadsheet program. Database queries were executed within Excel to obtain the required data from the database. Excel was then used to generate plots of various raw and derived performance metrics.

RAW DATA CONVERSION TO DATABASE

A common database structure was selected for storing the GPS receiver data so that all of the data could be accessed subsequently using the same basic utilities. However, the amount of data processing performed in the process of populating the database was minimized so that the databases would provide a reasonable representation of the actual output from the receiver. Therefore, certain differences among receivers in the units used to report various quantities were retained in the process of populating the database. For example, the receivers provided time outputs in a variety of formats [e.g., GPS seconds of week, universal time coordinated (UTC) time of day]. The time tags in the databases for each receiver are in whatever units were used by that receiver. Also, certain quantities were provided by some receivers but not by others. The database structure was designed to accommodate all of the data items extracted from all of the receivers (some data items were not deemed to be of interest and were not extracted for any of the receivers). Thus, certain fields in the databases contain data for some receivers but are empty for others. Despite these differences, the conversion from raw data files to databases allows the data for any receiver to be accessed using a Paradox database query.

Tables 3-1 to 3-3 summarize the structure of the databases and the raw data that was stored in each database field for each of the receivers. The database structure consists of three tables, identified as GPS.Main, GPS.Chan, and GPS.Code. The first column in Tables 3-1 to 3-3 lists the fields contained in each database table. The remaining columns list the receiver output data items that are stored in the corresponding database field.

Table 3-1 summarizes the structure of GPS.Main. This table was used to store quantities that were not SV-specific (e.g., position information, receiver clock offset). Each record for a given receiver is identified by a unique value of GPS.Main.Gtime. The Gtime field is the time output from the receiver.

Table 3-2 summarizes the structure of GPS.Chan. This table was used to store quantities that are SV-specific, but are not reported separately for the L_1 and L_2 signals in dual-frequency receivers (e.g., SV azimuth and elevation). Each record for a given receiver is identified by a unique combination of GPS.Chan.Gtime and GPS.Chan.Prn. The Gtime field is the same as in the GPS.Main table. The Prn field is the identifier for the SV to which the data in each record applies.

Table 3-3 summarizes the structure of GPS.Code. This table was used to store quantities that are SV-specific and are reported separately for L_1 and L_2 in dual-frequency receivers (e.g., pseudorange and carrier phase). Each record for a given receiver is identified by a unique combination of GPS.Code.Gtime, GPS.Code.Prn, and GPS.Code.Code. The Gtime and Prn fields are the same as in the GPS.Chan table. The Code field indicates whether the data in each record is for L_1 coarse acquisition (C/A) code, L_1 P code, L_2 P code, or codeless tracking.

Table 3-1. Structure of GPS.Main

Field	Receiver 1	Receiver 2	Receiver 3	Receiver 4	Receiver 6	Receiver 7
GTime	RGEA.seconds SATA.seconds	PBN.pbentime	GPGGA.utc	PBN.pbentime	RGEA.seconds	Type 0.receive time Type 1.gps ms of week
GWeek	RGEA.week SATA.week				RGEA.week	
Sitename		PBN.sitename		PBN.sitename		
Latitude			GPGGA.lat			Type 1.latitude
Longitude			GPGGA.lon			Type 1.longitude
Altitude			GPGGA.alt			Type 1.altitude
NaxX		PBN.navx		PBN.navx		
NaxY		PBN.navy		PBN.navy		
NaxZ		PBN.navz		PBN.navz		
NaxT		PBN.navt		PBN.navt		
NaxXDot		PBN.navxdot		PBN.navxdot		
NaxYDot		PBN.navydot		PBN.navydot		
NaxZDot		PBN.navzdot		PBN.navzdot		
NaxTDot		PBN.navtdot		PBN.navtdot		
PDop		PBN.pdop		PBN.pdop		
RecStatus	RGEA.rec status				RGEA.rec status	
SolStatus	SATA.sol status		GPGGA.GPS quality			Type 1.position flags
ClockOffset						Type 1.clock offset
FreqOffset						Type 1.freq offset
LatRate						Type 1.latitude rate
LonRate						Type 1.longitude rate
AltRate						Type 1.altitude rate

Table 3-2. Structure of GPS.Chan

Field	Receiver 1	Receiver 2	Receiver 3	Receiver 4	Receiver 6	Receiver 7
GTime	RGEA.seconds SATA.seconds	RPC.rcvtime		RPC.rcvtime	RGEA.seconds	Type 0.receive time
Prn	RGEA.prn SATA.prn	MPC.prn RPC.prn	GPGSV.prn	MPC.prn RPC.prn	RGEA.prn	Type 0.prn
El	SATA.elevation	MPC.elevation	GPGSV.elev	MPC.elevation		Type 0.elevation
Az	SATA.azimuth	MPC.azimuth	GPGSV.azimuth	MPC.azimuth		Type 0.azimuth
Residual	SATA.residual					
RejectCode	SATA.reject code					

Table 3-3. Structure of GPS.Code

Field	Receiver 1	Receiver 2	Receiver 3	Receiver 4	Receiver 6	Receiver 7
GTime	RGEA.seconds SATA.seconds	RPC.rcvtime			RGEA.seconds	Type 0.receive time
Prn	RGEA.prn SATA.prn	Separate records for L_1 C/A, L_1 P, and L_2 P	GPGSV.prn	Separate records for L_1 C/A, L_1 P, and L_2 P	RGEA.prn	Type 0.prn
Code	CA on L_1 assumed	Separate records for L_1 C/A, L_1 P, and L_2 P	C/A on L1 only	Separate records for L_1 C/A, L_1 P, and L_2 P	CA on L1 assumed	Separate records for L_1 C/A, L_1 P, and L_2 P
Warning		MPC.warning		MPC.warning		Type 0.flags1
Quality		MPC.quality		MPC.quality		Type 0.flags1
CNo	RGEA.C/No	MPC.S/N	GPGSV.SNR	MPC.S/N	RGEA.C/No	Type 0.SNR
CycleSlip		RPC.WN				Type 0.flags1
PseudoRange	RGEA.psr	MPC.raw range		MPC.raw range	RGEA.psr	Type 0.p range
PseudoRangeSTD	RGEA.psr std				RGEA.psr std	
PseudoRangeRPC		RPC.PL1/2				
CarrierPhase	RGEA.adr	MPC.carrier phase		MPC.carrier phase	RGEA.adr	Type 0.continuous phase
CarrierPhaseSTD	RGEA.adr std				RGEA.adr std	
CarrierPhaseRPC		RPC.PH				
Doppler	RGEA.dopp	MPC.Doppler		MPC.Doppler	RGEA.dopp	Type 0.doppler
LockTime	RGEA.locktime				RGEA.locktime	
TrackStatus	RGEA.ch-tr-status				RGEA.ch-tr-status	

CALCULATIONS AND PLOT GENERATION

Microsoft Excel provides a capability to query databases, and this capability was used to extract the GPS receiver data from the Paradox databases. Unit conversions for the various receivers were handled during the spreadsheet processing of the data. Also, the calculation of derived quantities (e.g., code minus carrier) was performed in the spreadsheets rather than during the population of the database.

The various raw and derived quantities were plotted as a function of test time. The plots provide a visual means of establishing when a particular effect occurred during a test. Because the conditions for each test are known as a function of test time, the test conditions that produced the identified effect can be established from a lookup table. Examples of the plots generated in this analysis effort are included Section 5.